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Research papers

Challenges and impacts of climate change and human activities on groundwater-dependent ecosystems in arid areas – A case study of the Nalenggele alluvial fan in NW China

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ABSTRACT

Desert oases exist around the alluvial fans of inland river basins in arid areas, where the vegetation growth is wholly dependent on groundwater due to scanty rainfall and arid environment. Climate change and water resources exploitation may threaten the groundwater-dependent ecosystems (GDEs) in the arid areas; a case study was proposed to evaluate the vegetative growth state with the normalized difference vegetation index (NDVI), hydrometeorological data, and the exploitation of water resources of the Nalenggele alluvial fan in northwest China. Climate change, and increasing temperature and precipitation may be indispensable factors for vegetation growth; however, based on the results of a correlation analysis, it was found that climatic factors shared little direct correlation with the NDVIs of the Nalenggele alluvial fan. Also, the depth to groundwater table (DWT) and distribution of shallow groundwater (DSG) are the direct influencing factors of vegetation growth. DWT and DSG are mainly controlled by the groundwater recharge mechanism and the original water sources from snowmelt, which are directly correlated with climate change. Predictions for DWT and DSG were made considering water resource exploitation and different river discharges amid climate change. The results reveal that the distribution area of shallow groundwater with the ecological water level (DWT $<$ 4 m) in 2020 will decrease to approximately 78–86% of that in the status quo year, which suggests vegetation may be at risk of degradation from the combined influence of climate change and human activities. Therefore, management strategy and legislation for protecting GDEs should be proactively initiated in other similar areas in China.

1. Introduction

Vegetation in a desert oasis, which exists mostly around the alluvial fan of its arid inland river basin, is highly dependent on groundwater due to the scanty rainfall and high levels of evaporation in the region. At least 30% of all global vegetation communities in dry lands use groundwater as their main supplement (Fan et al., 2013); most of the groundwater-dependent ecosystems (GDEs) rely on the distribution of shallow groundwater (DSG) and depth to groundwater table (DWT), which are the two key factors influencing vegetation growth in arid areas (Meinzer, 1927; Naumburg et al., 2005; Huntington et al., 2016). Changes in the DSG and DWT of GDEs, which are controlled in part by groundwater recharge and human exploitation, are the main factors affecting the vegetation; and generally, decline of groundwater levels cause the degradation of vegetation (Summers, 2001; Halford, 2015; Huntington et al., 2016).

Meanwhile, climate change and human activities directly and indirectly affect the GDEs by altering the water cycle, as well as the quantity and quality of groundwater and ecological functions (Li et al., 2018). Variation of vegetation coverage in the GDEs is sensitive to climatic factors (Jin et al., 2014). Climate change with increased air temperature, atmospheric water vapor, and greenhouse gases is known to have a continuous and significant impact on the vegetation (Pan et al., 2018). As a result of climate change, global temperature has increased over the past 60 years by approximately 0.49–0.89 °C, according to a report from the Intergovernmental Panel on Climate Change (IPCC, 2013) in 2013. Water conditions in some arid areas were improved by the increased summer precipitation and glacial melt as a result of global warming, and the ecological restoration has been partly improved in other areas and on multiple scales (Cheng et al., 2014; Hickler et al., 2006; Piao et al., 2006; Piao et al., 2013; Wolf et al., 2008), and climate change on vegetation ecosystems in the future will

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continue (Dai et al., 2016; Friend et al., 2014). However, global warming causes dry climate with decreasing precipitation, which puts the GDEs at high risk and makes them vulnerable (Barron et al., 2012; Iyalomhe & Idogho, 2016; Han et al., 2018). Furthermore, human activities such as groundwater regime alteration, agricultural disturbance, overgrazing, and grassland reclamation have caused degradation of vegetation (Elmore et al., 2003; Groeneveld, 2008; Yang et al., 2011; Pritchett and Manning, 2012; Nguyen et al., 2014; Homer et al., 2015; Liu et al., 2017; Kath et al., 2018). Vegetation characteristic is an important indicator that reflects the ecological situation; assessment of variation of vegetation coverage and the main control factors for GDEs in arid areas is pivotal for water resources utilization and ecological conservation.

The Nalenggele alluvial fan is typical of the dry climatic conditions that exist in the arid inland river basins of northwest China, where water resources and ecological systems have been in their natural state for the past several decades. Climate change and increasing human activities are impacting the fragile ecotopes of the GDEs in this area. A study found that the weather had become wetter in wet regions and drier in dry regions; particularly, precipitation levels had increased at high latitudes in the Northern Hemisphere but decreased in China (Walther et al., 2002; Wentz et al., 2007; Dore, 2005). Nevertheless, climate change exhibited a distinct pattern in the Qaidam basin—in the past 50 years, the temperature has increased by 2.0–2.5 °C at the rate of 0.51 °C/decade, and the annual precipitation increased at the rate of 6.2 mm/decade (Fu et al., 2011). The spatial distribution of climate change is different in different parts of the Qaidam basin. The annual mean temperature change decreased from the west part to the east part while the annual mean precipitation change exhibited the opposite trend (Fu et al., 2011; Li et al., 2015). Climate change coupled with the impending surge in river and groundwater utilization with the construction of the Qaidam Basin Circular Economy Experiment Area, and the vigorous exploration of mineral resources (Xu et al., 2017), will directly and indirectly influence the vegetation of GDEs in the Nalenggele alluvial fan. Therefore, this study aims to find out the tendency of variation of vegetation coverage, and evaluate the impact of climate change and human activities on the vegetation characteristics of GDEs in highly arid regions. Furthermore, it also suggests the management strategy and legislation required for protecting those GDEs.

2. Experimental methods

2.1. Features of study area

The Nalenggele River basin is located in the southwest Qaidam basin at the Qinghai province in northwest China (Fig. 1). Most of the region in the study area lies in the Gobi desert, and its elevation ranges from 2800 to 3500 m above sea level. A small human population inhabits the basin. The area is characterized by the typical climate of dry inland regions with scarce precipitation and intense evaporation. The average annual precipitation of the region in the last 50 years has been less than 30 mm/a, and has mainly occurred in summers, while the annual average evaporation rate is more than 2700 mm/a. The average annual temperature is approximately 3.0 °C with a maximum temperature of 35.3 °C and a minimum of −29.5 °C. A desert oasis exists around the edge of the alluvial fan in the shallow groundwater area and groundwater overflow zone.

2.2. Hydrometeorological data

Climate is a long-term average of the weather or meteorological elements (Pan et al., 2018). A long-term record of the meteorological data is used to study the climate change that influences the vegetation in this study area. Data from several national meteorological stations in the Qaidam basin was collected, the nearest meteorological station being Xiao Zaohuo. The monthly temperature and precipitation data of the study area from 1961 to 2016 were obtained from the National Meteorological Information Center of China (http://data.cma.cn).

2.3. Normalized difference vegetation index (NDVI) data

The normalized difference vegetation index (NDVI) has been widely used for assessing the ecological responses to long-time environmental change, climate change, and human activities (Peruelo and Lauenroth, 1998; Lu et al., 2003; Wardlow et al., 2007; Jacquin et al., 2010; Zhang et al., 2017; Xu et al., 2018). The value of NDVI is a ratio of the spectral reflectance difference between the near-infrared (NIR) and red bands to their reflectance summation. The NDVI can be used to assess the status of land surface vegetation. Large positive values generally indicate higher vegetation coverage, small positive values indicate low vegetation coverage, and negative and zero values indicate a water body or bare land (Lv et al., 2013). In this study, Landsat series images were used to estimate the NDVI considering its variation in the study area over the past 30 years. From 1986 to 2011, the Landsat 5 Thematic Mapper (TM) image was used; and from 2013 to 2016, the Landsat 8 Operational Land Imager (OLI) image was used. The NDVI can be described by the following equation:

$$NDVI = \frac{R_{NIR} - R_{RED}}{R_{NIR} + R_{RED}} \tag{1}$$

where R_{RED} and R_{NIR} represent the average reflectance measured in the visible (red) and near-infrared regions, respectively.

During the NDVI computation process on the remote image-processing system, ENVI®, spectral radiometric calibrations and atmospheric corrections were made for accuracy. Considering the spectral difference between Landsat 8 OLI and Landsat 5 TM (Table 1)—the results of the NDVI derived from the two types of remote-sensing images being slightly different (Pan et al., 2018)—the NDVI data should be carried on uniformization to compare the vegetation variation by the NDVI values in different years. The following equation constructed by Roy et al., 2016 with approximately 28 million, 30-m pixels extracted from 6317 Landsat 7 ETM+ and Landsat 8 OLI images was used to express the regression relationship between the NDVI derived from the two types of images. The wavelengths of NIR and Red bands of Landsat 5 TM are identical to those of Landsat 7 ETM+, and the equation below can also be used to describe the relationship between the NDVI derived from the Landsat 5 TM and Landsat 8 OLI images (Roy et al., 2016):

$$NDVI_5 = NDVI_7 = -0.011 + 0.969NDVI_8 \tag{2}$$

where $NDVI_5$, $NDVI_7$, and $NDVI_8$ represent the NDVI values derived from the Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI images, respectively.

The study area is located in a single-scene image with path number 138 and row number 34, and the image in each year was selected from the summer of June to August. All of the images with a 30-m resolution were downloaded from the Geospatial Data Cloud website supported by the Computer Network Information Center at the Chinese Academy of Sciences.

3. Results

3.1. Climatic characteristics

To investigate climate change in the Nalenggele alluvial fan region, the annual mean temperature, precipitation, and relative humidity from 1961 to 2016 were considered. The time-series plot of the annual mean temperature from the Xiao Zaohuo station is shown in Fig. 2, which demonstrates a significant increasing trend of the temperature in the study area with a confidence coefficient of 95%. On the other hand, the annual mean precipitation shows a slightly increasing trend (Fig. 3), but does not meet the required confidence coefficient of 95%, which means that the precipitation in the study area does not show a significant

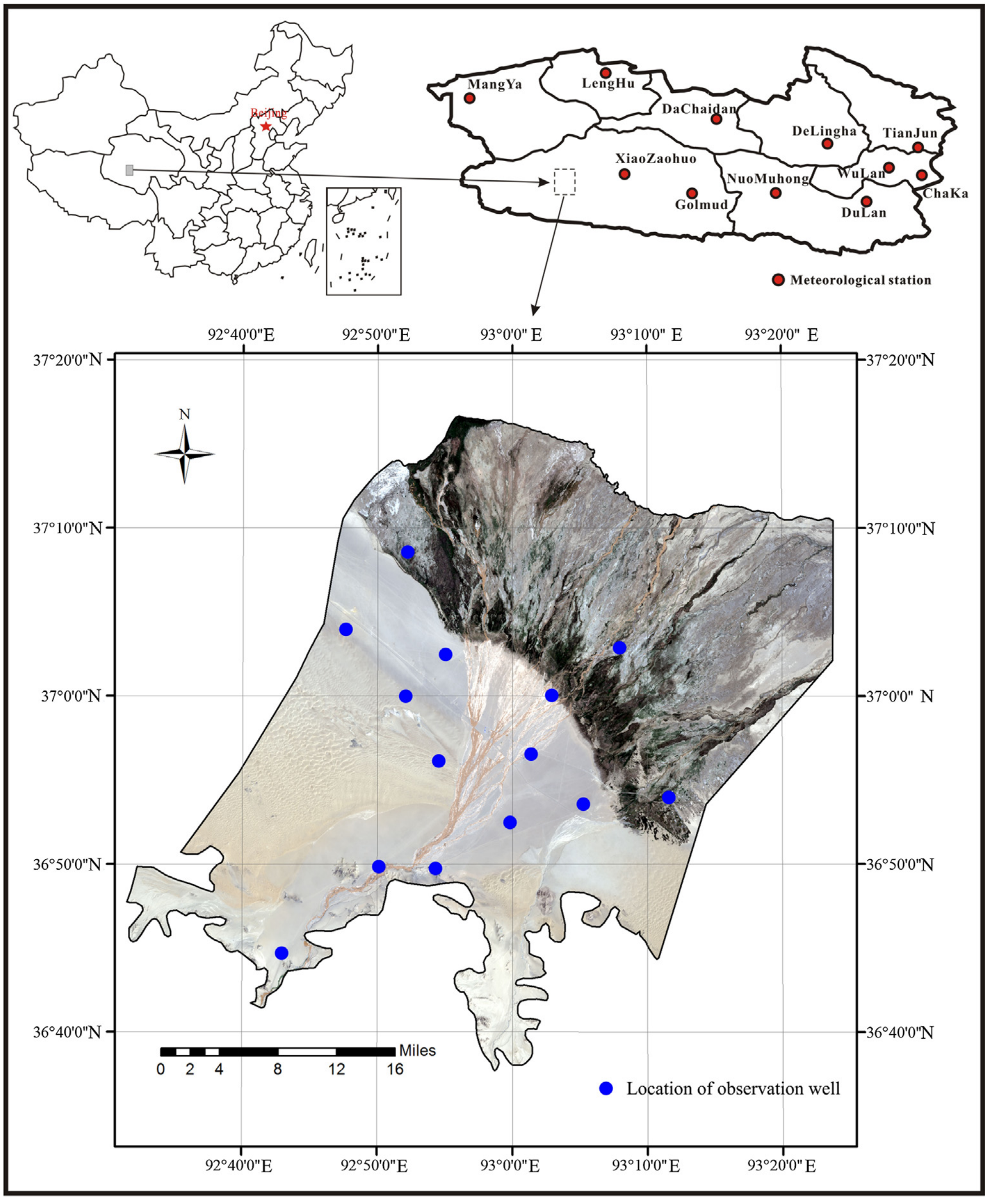

Fig. 1. Location of alluvial fan and meteorological stations in Qaidam Basin.

increase; this was also discussed by Fu et al. (2011).

Climate has an inevitable impact on the environment in which vegetation grows. Traditional hydrometeorological indicators such as precipitation, temperature, and humidity are widely considered as the main factors having an impact on vegetation growth (Ye et al., 2012; Shen et al., 2015). The climate of the study area during the past 55 years (1961–2016) had exhibited a significant warming and wetting trend, the rates of increase in temperature and precipitation are approximately 0.65 °C/decade and 2.1 mm/decade, respectively, and the climate regime has not changed significantly during the past 30 years (1986–2016). The monthly relative humidity from 1961 to 2016 showed a slightly decreasing tendency, which is the opposite of the increasing tendency of temperature and precipitation, and relative humidity showed an obvious increasing trend from 1986 to 2016, which is different from that from 1961 to 2016.

3.2. NDVI variation over the past decades

The NDVIs from 1986 to 2016 were derived from the Landsat scenes to evaluate the variation of vegetation coverage. The spatial distribution of the average NDVI from 1986 to 2016 shows that the alluvial fan was mainly covered by the lower NDVI values; majority of NDVI values

Table 1
Landsat spectral bands used for computing NDVI with different satellite.

Band	Landsat 5 TM		Landsat 7 ETM+		Landsat 8 OLI	
	Band Index	Wavelength (μm)	Band Index	Wavelength (μm)	Band Index	Wavelength (μm)
Red	Band 3	0.626–0.693	Band 3	0.626–0.693	Band 4	0.636–0.673
NIR	Band 4	0.776–0.904	Band 4	0.776–0.904	Band 5	0.851–0.879

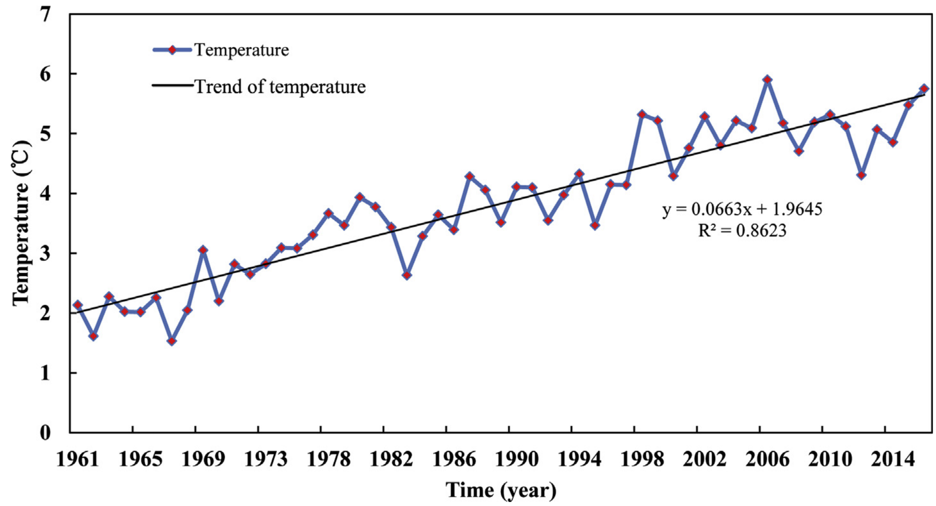

Fig. 2. Time-series plots of annual mean air temperatures in Xiaozaohuo meteorological station.

of the area is less than or equal to zero, because of the Gobi desert, sand dunes, and river water, which cover approximately 75% to 80% of the study area.

The positive NDVI value, which indicates the existence of vegetation cover, was used to express the variation of vegetation coverage during the past 30 years. During the field survey in July 2011, it was found that the land with continuous coverage of high density vegetation has an NDVI value greater than 0.2; the computed NDVI in the study area and the field survey results in 2011 are shown in Fig. 4. Typical NDVI values greater than 0.2, which were considered representative of high-density vegetation of the desert oasis in the past 30 years, cover only 0.10% to 11.52% of the study area (Fig. 5). The maximum and average NDVI values of all the positive NDVI values show an increasing trend from 1986 to 2016 (Fig. 6). The area proportions of positive NDVI values (NDVI > 0.2) also show an increasing trend (Fig. 5), which reflects the progressive tendency of vegetation growth.

In order to find a correlation between climate change and the temporal variation of the NDVIs, a correlation analysis involving the computation of correlation coefficients between the NDVI values and the climatic variables was conducted. Previous studies in regard to the vegetation of arid areas in northwest China have shown that the response of vegetation to temperature was intense amid climate warming, and the precipitation may not directly support the vegetation growth (Jin et al., 2014; Xu et al., 2018; Pan et al., 2018). From the results shown in Fig. 7, it can be seen that the increased temperature, precipitation, and relative humidity all contribute to the vegetation growth. The climatic variables also exhibit a certain correlation with the changing NDVI values in the past 30 years (1986–2016). However, all of the correlation coefficients are less than 0.5, which indicates the climatic variables did not have any significant impact on the variation of vegetation cover. All of the evidences suggest these climatic factors have little direct correlation with the NDVIs of the Nalenggele alluvial fan.

3.3. Correlation between vegetation and groundwater

Vegetation growth mainly depends on sunlight and water, which are the main ingredients of photosynthesis (Pan et al., 2018). As the growth season, energy from the sunlight falling on the Gobi desert is sufficient, the vegetation growth there depends mainly on the supply of soil water in the root zone. As discussed above, the study area is located in an extremely arid environment with an average annual precipitation of less than 30 mm and evaporation more than 2700 mm. Precipitation cannot recharge the water in the root zone or the aeration zone, and the shallow, buried groundwater could supply majority of the water demand for vegetation growth. The distribution of NDVI values during

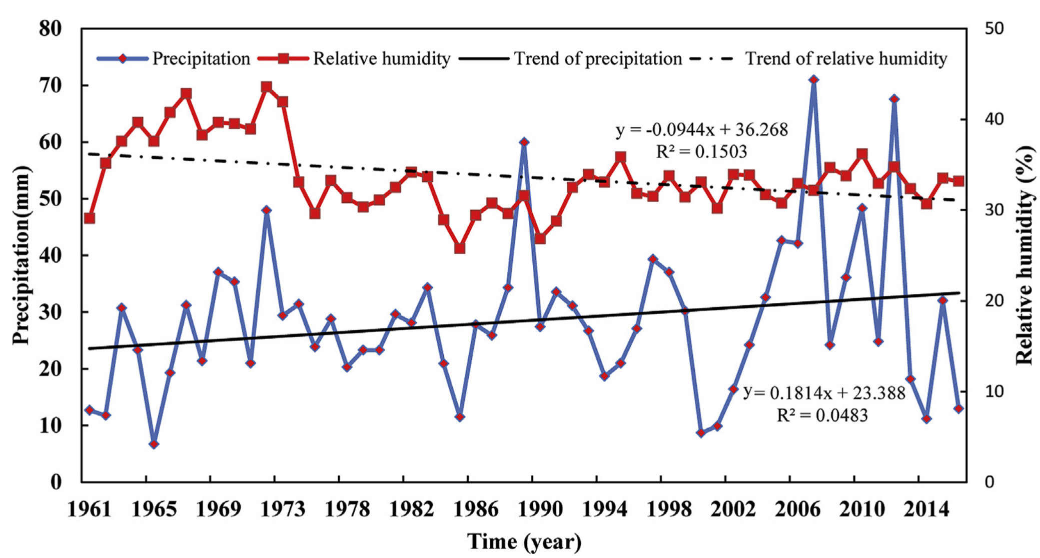

Fig. 3. Time-series plots of annual mean precipitations and relative humidity in Xiaozaohuo meteorological station.

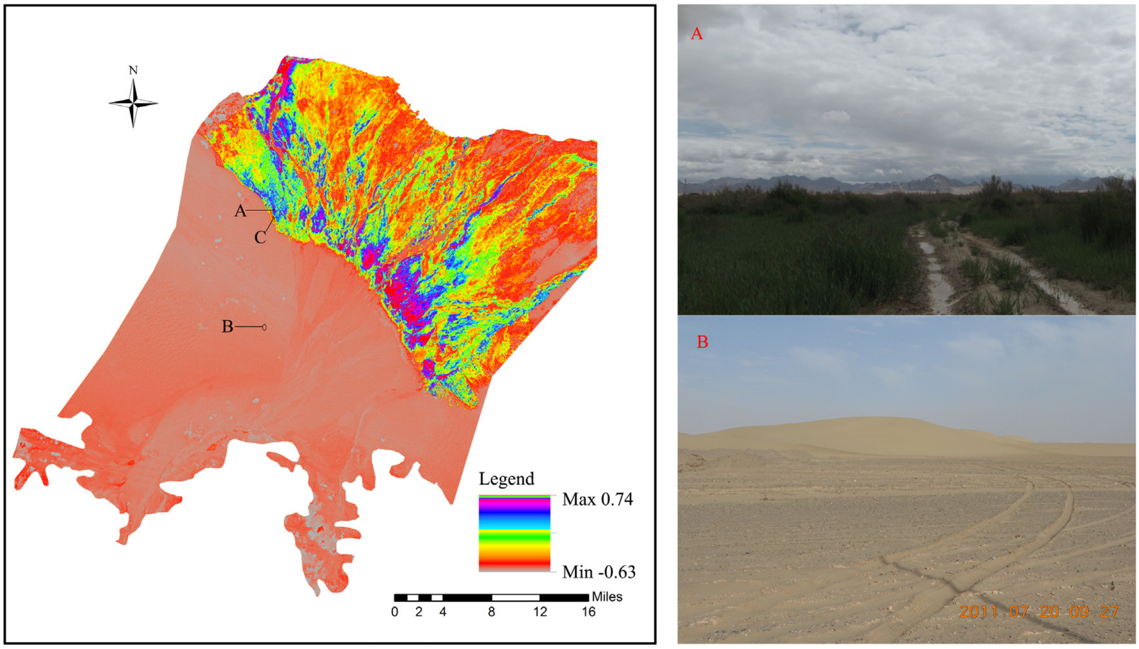

Fig. 4. Distribution of NDVI in July 2017 computed from Landsat 5 TM images. Two pictures showing the vegetation in the study area taken during the field survey; C is the location where the picture in Fig. 10 was taken at.

July 2011 is shown in Fig. 4, and the contour map of DWT in the same period obtained from observational data through the spatial interpolation method is shown in Fig. 8. From the spatial distribution of the NDVI values, which indicate land surface vegetation cover of the study area, it is clear that majority of the vegetation is distributed over the alluvial fan-fringe area with shallow, buried groundwater, and it greatly depends on DWT as well.

The values of NDVI and DWT in the same location were extracted, and the corresponding scatter diagram is shown in Fig. 9. The NDVI values range from −0.63–0.74 and the DWT values vary between 0.01 and 312.9 m. Approximately 76% of the data points are concentrated in the range of −0.63 < NDVI < 0, with the DWT range from zero to more than 300 m (part A in Fig. 9). The corresponding spatial location of the data points is distributed among the desert, the mountain area, and the oasis; another 24% of the data points are distributed in the range of 0 < NDVI < 0.74 (part B in Fig. 9). The location of the data points is distributed among the desert and oasis, with DWT ranging from 0 to 100 m. Data points with NDVI values greater than 0.2 are distributed among the areas with DWT ranging from 0 to 100 m (part C in Fig. 9), and the vast majority of data points are distributed among the areas with DWT less than 20 m (part D in Fig. 9). In addition, some of the NDVI values were negative in the shallow groundwater area, which could be due to the intense soil salinization in this area, and the soil salinization was confirmed during a field survey (Fig. 10).

4. Discussions

4.1. Impact of changing environmental conditions on GDEs

The vegetation characteristics may be attributed to the combined influence of multiple factors, including climate, soil cover, and hydrogeological features (Jin et al., 2011; Lv et al., 2013). Based on the above

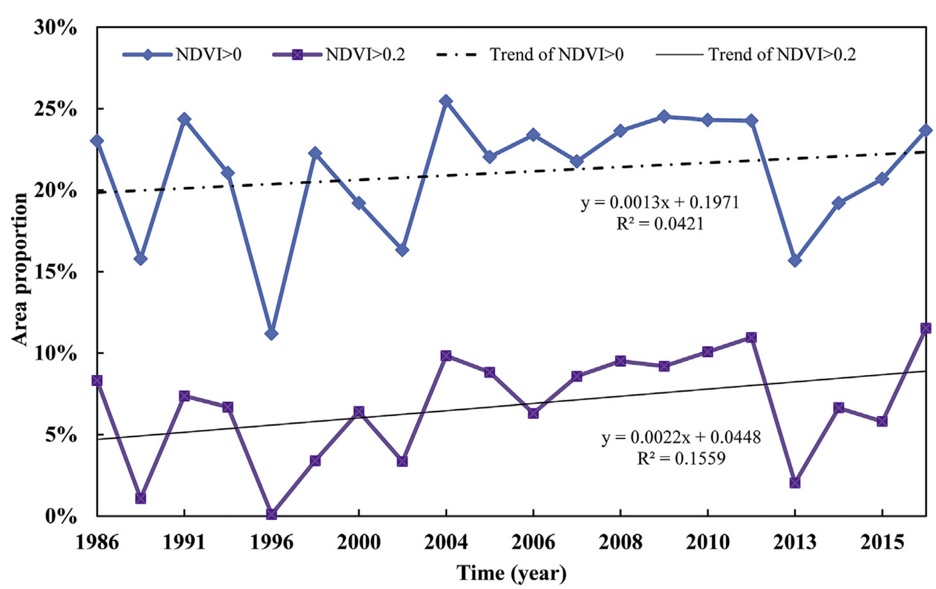

Fig. 5. Variation of area proportion under different typical NDVI values during the past 30 years.

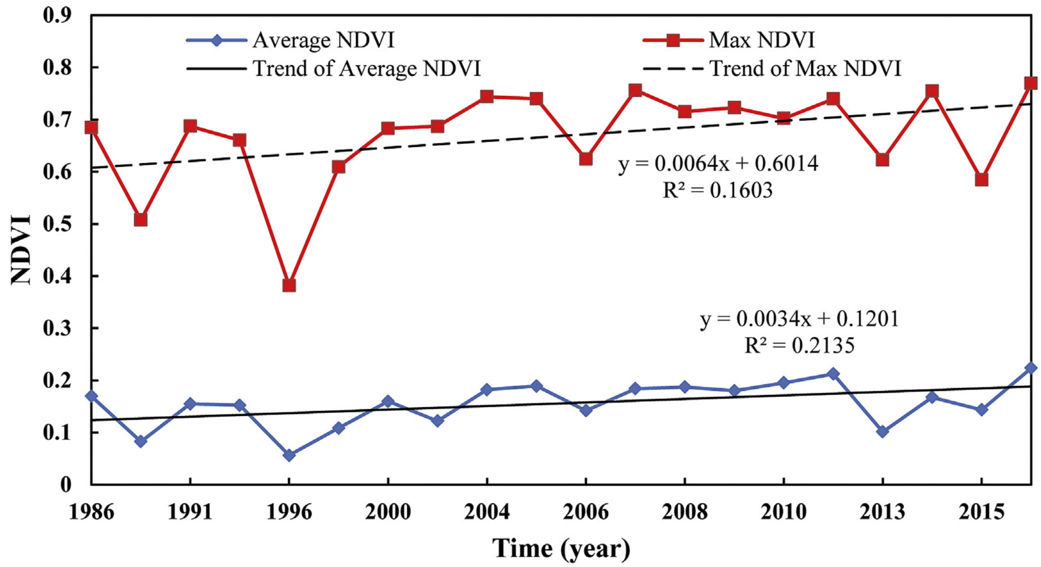

Fig. 6. Variation of maximum and average NDVI values during the past 30 years.

discussion, it stands to reason that DWT should be the governing factor of vegetation in this area, and the DSG is controlled by groundwater recharge and exploitation. According to the previous studies, shallow groundwater in the alluvial fan of this area is mainly recharged by river infiltration, and the underground lateral flow that originates from the snowmelt and precipitation from the Kunlun Mountains (Su et al., 2015; Xu, 2015; Xu et al., 2017; Xiao et al., 2018). Groundwater recharge is directly related to the Nalenggele River discharge, which is controlled by the effective snowmelt in the mountain area, and the snowmelt runoff will increase with the rising temperatures as a result of climate change (Wang and Li, 2005).

Therefore, for future research groups to study the impact of climate change on vegetation, an established groundwater flow numerical simulation model was used to predict the distribution of groundwater level (Xu, 2015). Several scenarios were proposed with the consideration of different river water discharges related to climate change and water resource exploitation. Long time-series runoff data could not be monitored because the hydrometric station was set up for only four years during the 1960s. The river discharge data in 1960–1963 were monitored by the hydrologic institution, and the data in 2009, 2011, and 2012 were monitored by the researchers during field surveys. It is impossible to establish the relations between river discharge and climate change; the maximum, average, and minimum river discharges in 1960 to 1963, 2009, and 2011 to 2012 were used to express the river discharge of high, normal, and low-flow years under the control of changing climate; approximately 53% of the river discharges infiltrate and recharge the groundwater (Xu, 2015; Xu et al., 2017). The quantity of water resource exploitation was determined based on the requirements of the existing water-intake project and water resources planning. The exploitation of groundwater includes a water source site and water demand from some mineral enterprises. In this project, the river water is supplied to agricultural irrigation by a diversion canal (Zhang et al., 2014). Three scenarios with extreme conditions have been proposed to simulate the river discharge: **Scenario A:** sustained high temperature causes river discharge under the high-flow condition, with a flow quantity of $20.1 \times 10^8\,m^3/a$, from 2011 to 2020. **Scenario B:** sustained normal temperature causes river discharge under the normal-flow condition, with a flow quantity of $12.9 \times 10^8\,m^3/a$, from 2011 to 2020. **Scenario C:** sustained low temperature causes river discharge under the low-flow condition, with a flow quantity of $8.73 \times 10^8\,m^3/a$, from 2011 to 2020. Exploitation of groundwater and river from 2011 to 2020 is $0.40 \times 10^8\,m^3/a$ and $2.15 \times 10^8\,m^3/a$ in each scenario; the detailed information of the scenarios are shown in Table 2. The prediction model was tested under various input conditions, and the depths to groundwater table for 2020 in different scenarios are shown in Fig. 11.

Groundwater availability for vegetation growth determines the correlation between vegetation and DWT variation, which is controlled by a limitation of DWT. This limitation is the ecological water level that was discussed for different areas with arid conditions similar to that of the Nalenggele alluvial fan. An ecological water level of 10 m was confirmed as the limitation of DWT in the semi-arid Hailiutu River catchment area of China (Lv et al., 2013), and a similar limitation (8–10 m) has also been established in Australia at multiple sites (Zencich et al., 2002; Benyon et al., 2006; O'Grady et al., 2006). In the Ejina area of China, the suitable DWT limitation was found to be 2.8–5.0 m (Jin et al., 2011). The limitation of DWT in the Mahai River basin of the Qaidam Basin and in the desert oasis of the Hexi Corridor areas was found to be approximately 3.0–4.5 m (Zhao et al., 2003; Liu, 2014). The limitation of DWT is influenced by a combination of floral species, soil cover, and climatic characteristics. In this study, the DWT of the boundary between the desert and the oasis is approximately 4.0 m, according to the field survey, and the depth might be the dividing limit considered as the limitation of DWT. The distribution of range area with DWT less than 4.0 m is highlighted in Fig. 11. The number of areas with DWT less than 4.0 m in different scenarios was counted and compared with that in the status year of 2011; the areas in scenarios A, B, and C are approximately 86%, 82.5%, and 78% of the areas in the status quo year, respectively, which means that the vegetation is at a risk of degradation from the combined influence of climate change and human activities. Temperature and precipitation were continuously increasing during the past years (Figs. 2 and 3), which was proven to have caused an increase of ice-snow melting and groundwater recharge. In the natural state, the groundwater flow system can attain a recharge–drainage balance due to the regulation and storage capacity of groundwater aquifers. Therefore, a decrease in DSG in the proposed scenarios should be caused by the disruption of groundwater flow balance, which is directly caused by water resource exploitation, and is a main reason behind the ecological degradation of GDEs.

4.2. Consideration of management strategy and legislation for protection of GDEs

GDEs are increasingly threatened by human-led exploitation of water resources, which often exceeds natural recharge rates (Gleeson et al., 2015; Rohde et al., 2017). Independent ecosystem protection or

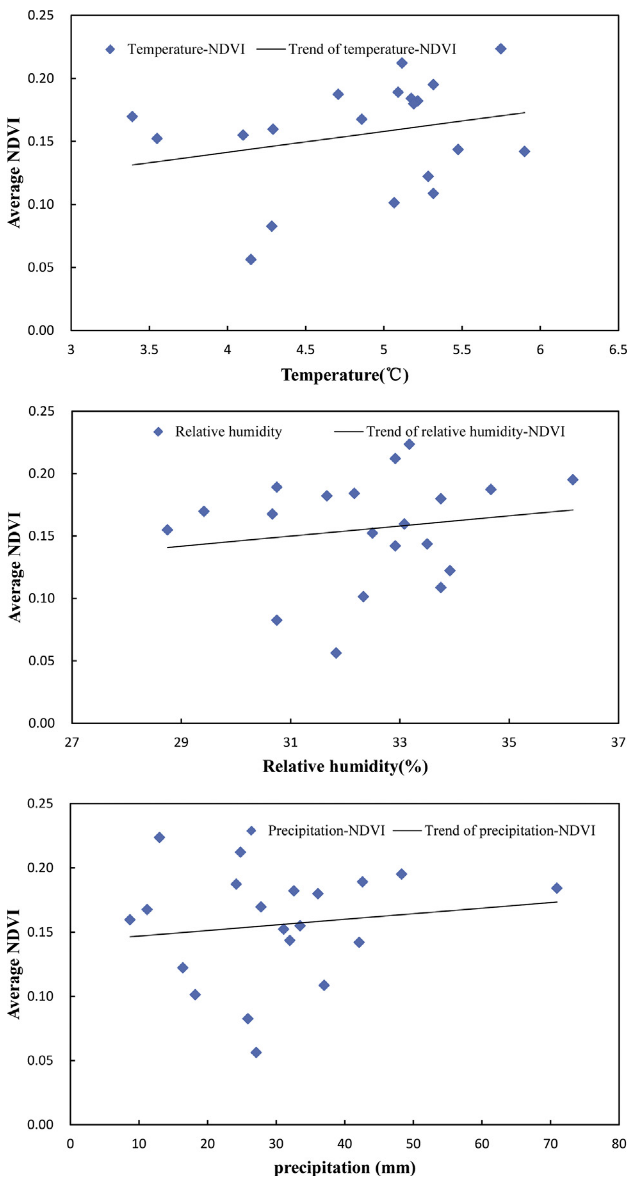

Fig. 7. Scatter plot of NDVI values and meteorological elements.

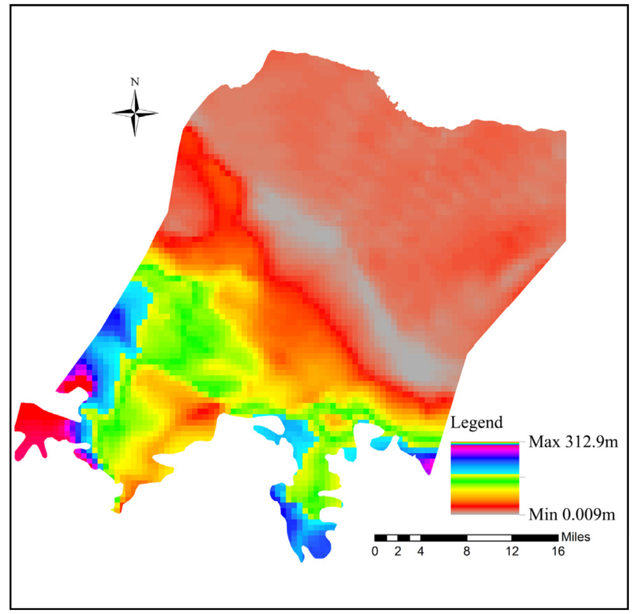

Fig. 8. Distribution of depth to water table (DWT) in July 2011.

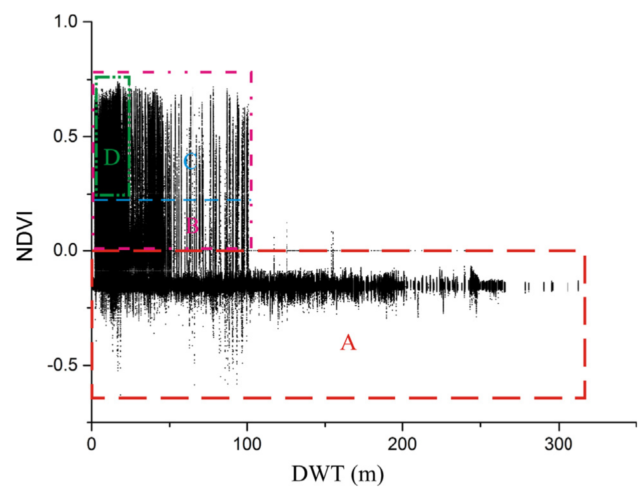

Fig. 9. Scatter plot of NDVI and DWT of the study area in July 2011. Part A is the area with scarce vegetation all over the study area; Part B is the area with vegetation and DWT less than 100 m; Part C is the area with continuous coverage of high-density vegetation; Part D is the area with high density vegetation and small DWT.

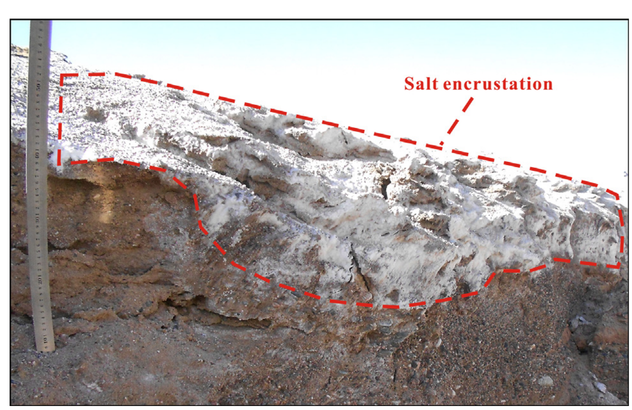

Fig. 10. Picture of salinization of soil in the study area taken during the field survey. The picture was taken in July 2011 near the boundary of the desert oasis. The location is represented in Fig. 4 with point C.

included underwater management strategy and legislation is one of the solutions for ensuring ecological health and sustainability of GDEs. There has not been any recent management strategy and legislation implemented in this area in China. Concerned authorities should educate themselves from the experiences of others. For example, adaptive management, which is at the core of Australia's approach for managing GDEs, utilizes ongoing monitoring and research to inform management decisions for determining the hydrologic conditions and thresholds required to maintain a GDE (Richardson et al., 2011; Serov et al., 2012). The "learning by doing" form of adaptive management strategy is suitable for the area of blank data monitoring and legislative supervision. An iterative process from primal conceptualization to filling the knowledge gaps in the study of GDEs, combined with the internationally recognized concept of "precautionary principle," would be the purport of GDEs protection under the adaptive management strategy. Ecological water requirements, which include threshold value of depth to water table targets, water quality standards, and flow dynamic criteria at the boundary of interconnected surface water bodies (Rohde et al., 2017), are the key elements in GDEs management strategy formulation. The determination of thresholds for GDEs still remains a challenge for water management authorities, largely due to

Table 2
Information of river discharge and water resource exploitation scheme.

Scenario	River discharge and hydrologic regime (m^3/a)	Groundwater exploitation (m^3/a)	River water exploitation (m^3/a)
Scenario A	20.1×10^8 with continuous high-flow year	0.40×10^8	2.15×10^8
Scenario B	12.9×10^8 with continuous normal flow year	0.40×10^8	2.15×10^8
Scenario C	8.73×10^8 with continuous low-flow year	0.40×10^8	2.15×10^8

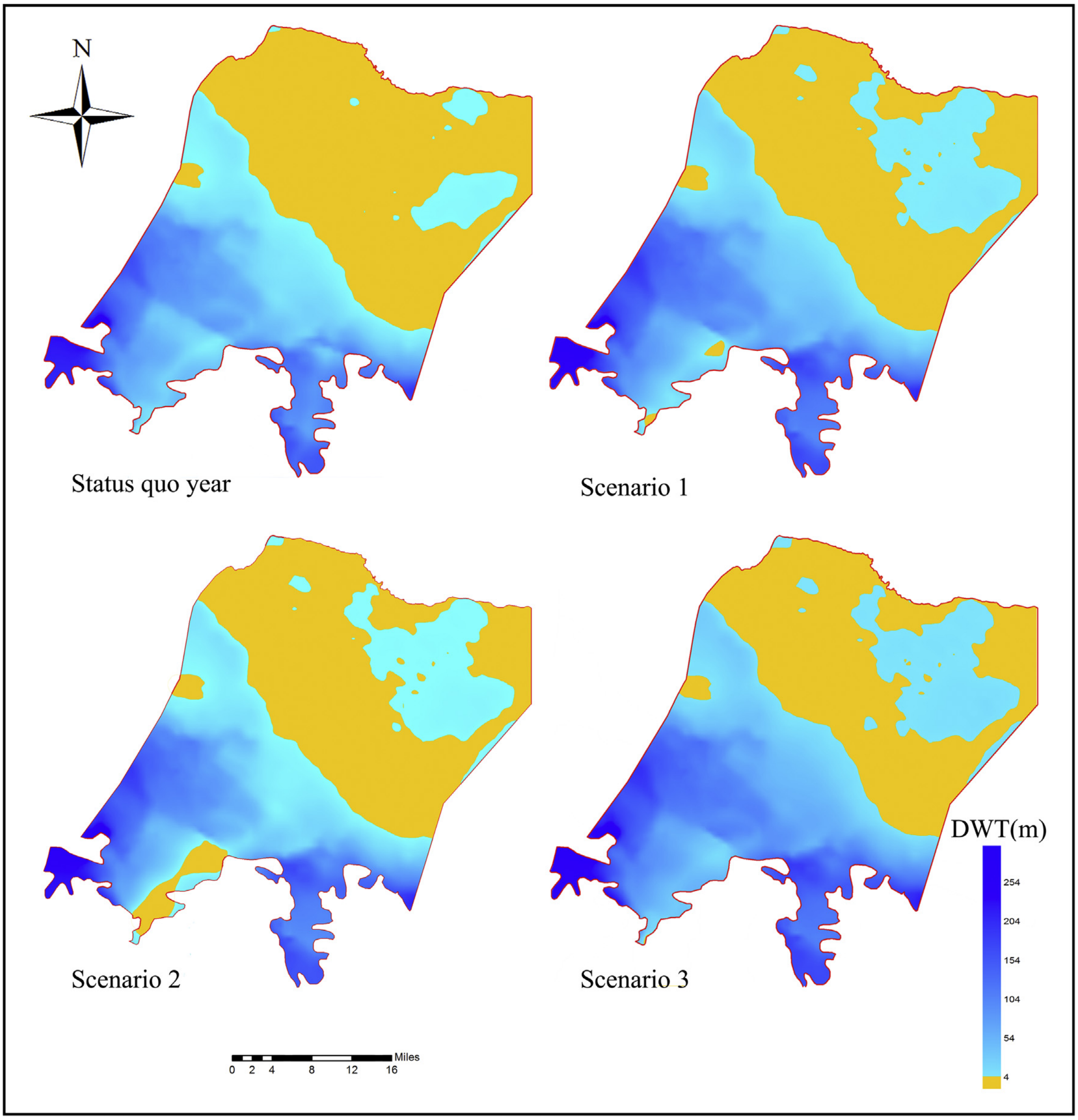

Fig. 11. Distribution map of DWT and shallow groundwater area in different scenarios.

the knowledge and information gaps present in the ecohydrology of the study area. It is important for managers to integrate the biotic and abiotic factors of the GDEs into local monitoring work; understanding the abiotic factors including groundwater recharge mechanism and groundwater level, water quality, and groundwater-surface water interaction, and biotic factors including ecosystem structure, species composition, reproduction, and growth are the essential prerequisites for GDE protection. Risk assessments are required in the interim to prevent any adverse consequences of management actions that replying the natural resources exploitation and climate change. Legislators of natural resources management can achieve these local needs by leveraging additional assistance from research institutions, and legislation and management strategy formulations are both interrelated. In addition, a coordinated approach of common frameworks and methodological approaches need to be mulled to promote overall success in the implementation of legislation (Rohde et al., 2017).

5. Conclusions

This study was conducted with an aim to assess the impacts of climate change and human activities on vegetation in groundwater-dependent ecosystems in arid areas. Long time-series meteorological data and NDVI values were used to recognize the changing trend of climate change and variation of vegetation coverage during the past several

decades. From 1986 to 2016, the climate showed a warming and wetting trend, and the variation of NDVI values showed an increasing trend, which could indicate a progressive trend in vegetation growth. However, all of the climatic factors in the Nalenggele alluvial fan were found to have little direct correlation with the NDVIs of the region. Groundwater is the major source of water for vegetation growth in arid areas. The distribution of shallow groundwater, which is under the control of groundwater recharge mechanism, determines the vegetation growth in the alluvial fan. The warming temperature will cause an increasing trend of snowmelt runoff, and the river discharge and infiltration to groundwater will increase, both of which could cause an increase in the shallow groundwater area. However, human activities involving groundwater and river water exploitation will be counterproductive in some cases. A prediction was made to tackle the situation; three scenarios were proposed with the consideration of river discharges and water resources exploitation, and the results showed that the distribution of shallow groundwater with the ecological water level (DWT $<$ 4 m) in 2020 will decrease to approximately 78–86% of the status quo year. Although vegetation growth in this area during the past several decades has been improving amid climate change, the intervention of human activities will inevitably hinder the otherwise advantageous processes of vegetation growth in GDEs. Thus, proper management strategy and legislation for GDE protection must be ratified to meet the challenges of human-accelerated climate change and increasing demand of naturel resources.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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